

LHC phenomenology of general $SU(2) \times SU(2) \times U(1)$ models

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(Dated: March 1, 2013)

General $SU(2) \times SU(2) \times U(1)$ models represent a well-motivated intermediate step towards the unification of the Standard Model gauge groups. Based on a recent global analysis of low-energy and LEP constraints of these models, we perform numerical scans of their various signals at the LHC. We show that total cross sections for lepton and third-generation quark pairs, while experimentally easily accessible, provide individually only partial information about the model realized in Nature. In contrast, correlations of these cross sections in the neutral and charged current channels may well lead to a unique identification.

INTRODUCTION

The Standard Model (SM) of particle physics is very successful in describing a wealth of experimental data, but is widely believed to be incomplete. One of the reasons is that it reposes on the *ad hoc* gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ with three unrelated factors, of which the second one violates parity, while the third one depends on the unphysical hypercharge. Their unification in a larger, simple group is theoretically very attractive. Beyond minimal $SU(5)$, already ruled out from proton decay, the possible unification groups have a rank larger than the SM and thus also contain additional subgroups like $U(1)$ or a second $SU(2)$, which lead to additional neutral and charged gauge bosons. These so-called Z' and W' bosons are actively searched for at the Large Hadron Collider (LHC) at CERN. Importantly, the discovery of a W' boson naturally implies the existence of a Z' boson, but not vice versa.

While the recent discovery of non-zero neutrino masses, possibly generated by a see-saw mechanism, and the prospect of parity restoration point in the direction of a left-right (LR) symmetric group containing a $SU(2)_R$, the large hierarchy in the mass spectrum of the SM fermions motivates fermion un-unified (UU) or generation non-universal (NU) groups $SU(2)_2$ and $SU(2)_1$, broken at high and low (SM-like) vacuum expectation values (VEVs) u and v . In general, a large variety of models with a second $SU(2)$ subgroup exist. Often denoted as G(221) models, they also appear naturally in larger unification groups like $SO(10)$ and E_6 and in many string theory compactifications and can be classified according to their symmetry breaking pattern [1]. Identification of $SU(2)_1$ with the one of the SM implies in the simplest scenarios the breaking scheme $SU(2)_2 \times U(1)_X \rightarrow U(1)_Y$ at the scale u through a Higgs doublet (D) or triplet (T). This scheme applies not only to LR [2], but also leptophobic (LP), hadrophobic (HP) and fermiophobic (FP) models [3]. In contrast, identification of $U(1)_X$ with the hypercharge group of the SM

as in the UU [4] and NU [5] models leads to the breaking scheme $SU(2)_1 \times SU(2)_2 \rightarrow SU(2)_L$ through a bi-doublet Higgs at the scale u with the immediate consequence of $M_{Z'}^2/M_{W'}^2 = 1 + \mathcal{O}(v^2/u^2)$. Parameterizing the model dependence in terms of the tangent of the mixing angle $\tan \phi = g_X/g_2$ (LR, LP, HP, FP) or g_2/g_1 (UU, NU) at the first breaking stage, the ratio of the squared Higgs VEVs $x = u^2/v^2$, and the alignment angle β of the light Higgs fields in the case of the first breaking pattern, Hsieh *et al.* have been able to perform a global analysis of low-energy and electroweak precision data with an effective Lagrangian approach [1], which resulted essentially in lower bounds on the masses of the Z' and W' bosons.

At the LHC, information about extended gauge symmetries can be obtained from cross section measurements, *e.g.* of pairs of leptons [6] or top quarks [7] or their associated production with W' bosons [8], or measurements of the top quark polarization [7, 9, 10]. In this Letter, we demonstrate that total cross sections for lepton and third-generation quark production, while easily accessible at the LHC, allow for a unique identification of the correct G(221) model only when correlated among each other in the neutral current (NC) and charged current (CC) channels. In the following section, we summarize the theoretical assumptions and experimental constraints that have entered our analysis. We then describe the setup of our simulations and present our numerical results for the total LHC cross sections and their correlations. Our conclusions are given in the last section.

THEORETICAL ASSUMPTIONS AND EXPERIMENTAL CONSTRAINTS

We assume that the LHC will operate after the 2013-2014 shutdown at its design center-of-mass energy of $\sqrt{s} = 14$ TeV and accumulate an integrated luminosity of 10 to 100 fb^{-1} , so that cross sections down to 10^{-2} fb can be observed. In the Sequential Standard Model (SSM) [11], which (although physically unmoti-

vated) is often taken as a benchmark scenario, the Z' and W' bosons would then be accessible up to masses of 5 TeV [12], while with present ATLAS (CMS) data masses below 2.21 (1.94) [13, 14] and 2.15 (2.27) TeV [15, 16] are excluded in the leptonic channels. We assume one of these bosons to have been observed in at least one channel and its mass to have been measured from the invariant mass of a lepton (e , μ), $t\bar{t}$, or $t\bar{b}$ pair or the Jacobian peak of the transverse mass of a single lepton and missing transverse energy as 3.0 ± 0.1 TeV or 4.0 ± 0.1 TeV with a conservative error estimate [12] [29]. Since the cross section times branching ratio to electrons and muons in the SSM is about six times larger for W' than for Z' bosons, the former may well be discovered first [17], but this order is not essential to our study.

Apart from the W' or Z' mass, we impose the global constraints mentioned above [1], which we parameterize in terms of $\tan\phi$ and the mass of the other new gauge boson. We translate these constraints through an interaction Lagrangian

$$\begin{aligned} \mathcal{L} = & \frac{g_L}{\sqrt{2}} \left[\bar{u}_i \gamma^\mu \left((C_{q,L}^{W'})_{ij} P_L + (C_{q,R}^{W'})_{ij} P_R \right) d_j \right. \\ & \left. + \bar{\nu}_i \gamma^\mu \left((C_{l,L}^{W'})_{ij} P_L + (C_{l,R}^{W'})_{ij} P_R \right) e_j \right] W'_\mu \\ & + \frac{g_L}{c_\theta} \left[\sum_q \bar{q}_i \gamma^\mu \left((C_{q,L}^{Z'})_{ij} P_L + (C_{q,R}^{Z'})_{ij} P_R \right) q_j \right. \\ & \left. + \sum_l \bar{l}_i \gamma^\mu \left((C_{l,L}^{Z'})_{ij} P_L + (C_{l,R}^{Z'})_{ij} P_R \right) l_j \right] Z'_\mu \quad (1) \end{aligned}$$

into bounds on the left- and right-handed coupling constants $C_{L,R}$, where the sums extend over up- and down-type quark flavors and over neutrinos and charged leptons, respectively. Scanning over the allowed parameter space we then obtain predictions for the lepton (e or μ) and third-generation (t or b) quark production cross sections.

The global constraints have been obtained on the basis of a number of theoretical assumptions, in particular generation-diagonal, perturbative gauge couplings (smaller than $\sqrt{4\pi}$), minimal (doublet, triplet or bi-doublet) Higgs sectors with a hierarchy of VEVs ($u \gg v$), validity of the Appelquist-Carazzone decoupling theorem, and negligible influence of additional fermions required, *e.g.*, for the cancellation of gauge anomalies. Fixed reference observables were the electromagnetic fine structure constant α , the Fermi constant G_F determining v^2 , and the mass of the SM Z boson M_Z fixing the tangent of the weak mixing angle $s_\theta/c_\theta = g_Y/g_L$. Similarly to the SM analysis of the Particle Data Group (PDG) [18], the three free parameters were fit to 37 observables, of which the most important ones were the total hadronic cross section at the Z pole, the b -quark forward-backward asymmetry, the neutrino-nucleon deep inelastic scattering cross section, and the parity-violating weak charge of

Caesium 133. Low-energy constraints like $\text{BR}(b \rightarrow s\gamma)$ requiring information on the extended flavor structure of the models (*e.g.* the right-handed CKM matrix) were voluntarily omitted. Fixing the top quark and light Higgs-boson masses to their SM best-fit values had little influence on the results, which led to lower bounds on the Z' and W' masses ranging from 0.3 to 3.6 TeV depending on the particular G(221) model.

LHC PHENOMENOLOGY

Total cross sections for the production of W' and Z' bosons decaying into leptons and third-generation quarks have been simulated with the Monte Carlo program **Pythia 6.4** [19], which we have supplemented by terms accounting for the interferences of new and SM charged bosons. While the latter can have a significant influence on the shape of the resonance region, their impact on the total cross sections is small. Monte Carlo generators including next-to-leading order (NLO) QCD corrections exist, but only for leptonically decaying Z' and W' bosons [20, 21], so that we have not made use of them in this study for consistency. Furthermore, these corrections are modest (typically about 30%) and largely model-independent, so that they would shift all contours in the same direction and not change our conclusions. The masses of the t and b quarks and SM Z and W bosons are fixed to their PDG values [18], and we use the CTEQ6 LO analysis of parton density functions (PDFs) [22]. For a study of the PDF uncertainties on SM and new weak gauge boson production cross sections we refer the reader to Ref. [23].

Following the ATLAS leptonic analyses [13, 15], we require electrons to have transverse energy $E_T > 25$ GeV and lie within the rapidity ranges $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$. For $\ell\nu$ final states, a missing energy $E_T^{\text{miss}} > 25$ GeV is imposed. In the third-generation quark channels, the ATLAS collaboration reconstruct jets with the anti- k_T algorithm and a radius of $R = 0.4$ and require them to have $E_T > 20$ GeV and $|\eta| < 4.5$ [24]. The total cross sections are then still largely dominated by SM backgrounds, simulated also using **Pythia 6.4**, which we suppress by imposing an invariant or transverse mass larger than 75% of the known new gauge boson mass.

In Fig. 1 we show the resulting total CC (left) and NC (right) cross sections in the lepton (top) and third-generation quark (bottom) channels. In all models, including the SSM shown for comparison, they are now by up to two orders of magnitude larger than the SM background (which now depends on $M_{W',Z'}$ due to the transverse and invariant mass cutoff, respectively), but still exceed 10^{-2} fb for masses up to 5 TeV. The shaded areas correspond to the ranges in parameter space still allowed after the global analysis of low-energy and LEP

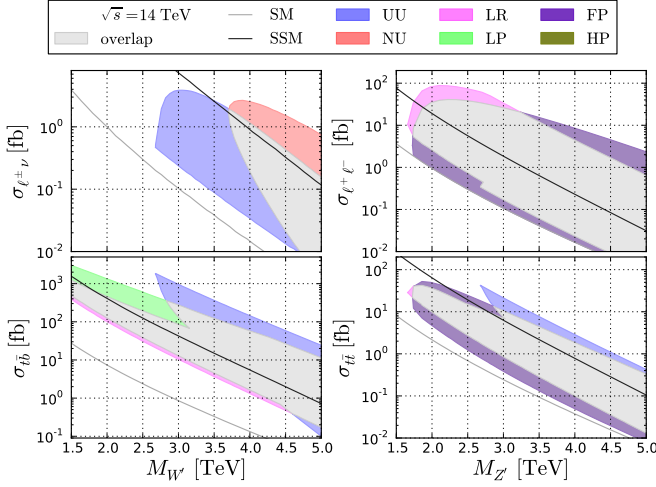


FIG. 1: Total CC (left) and NC (right) cross sections in the lepton (top) and third-generation quark (bottom) channels.

data. As one can observe, they exhibit a large overlap (grey). So while the cross sections are experimentally easily accessible, the pre-LHC constraints are clearly not strong enough to allow for an unambiguous identification of the gauge group possibly realized in Nature. The same applies to the Higgs sector of the LR (pink), LP (green), HP (purple), and FP (olive) models, for which regions with doublets and triplets are coded with the same color, as they overlap almost completely. For these models, we make no predictions for the lepton-neutrino channel, as we do not have any information about the right-handed neutrino sector. Applying a b -tag to the quark channels would reduce their cross sections by the corresponding efficiency of about 60% [24].

In Fig. 2 we now correlate the total cross sections with each other assuming either a known mass of $M_{W'} = 3.0 \pm 0.1$ TeV (top, center) or of $M_{Z'} = 3.0 \pm 0.1$ TeV (top, bottom). The shaded areas correspond now to the regions of parameter space allowed by the global fit and in addition the uncertainty in the mass of the observed gauge boson. As already discussed in the introduction, for the UU and NU models $M_{W'} \simeq M_{Z'}$. For the other models (LR, LP, FP, HP), we compute the mass that has not been fixed. More specifically, for the middle row $M_{Z'}$ is computed as a function of $M_{W'}$ and the other parameters at each point of the allowed parameter space [1]. Similarly, for the bottom row $M_{W'}$ is determined as a function of $M_{Z'}$ and the other parameters. Should the uncertainty be only 0.05 instead of 0.1 TeV, the width of these bands shrinks by more than a factor of two, turning them almost into sharp lines. As the plots in the first line always involve the lepton-neutrino channel and as masses below 3.6 TeV are already excluded for the NU model [1] (cf. also Fig. 1), we show there only predictions for the UU model. With signal cross cross sections that are one to three orders of magnitude larger than those of the SM

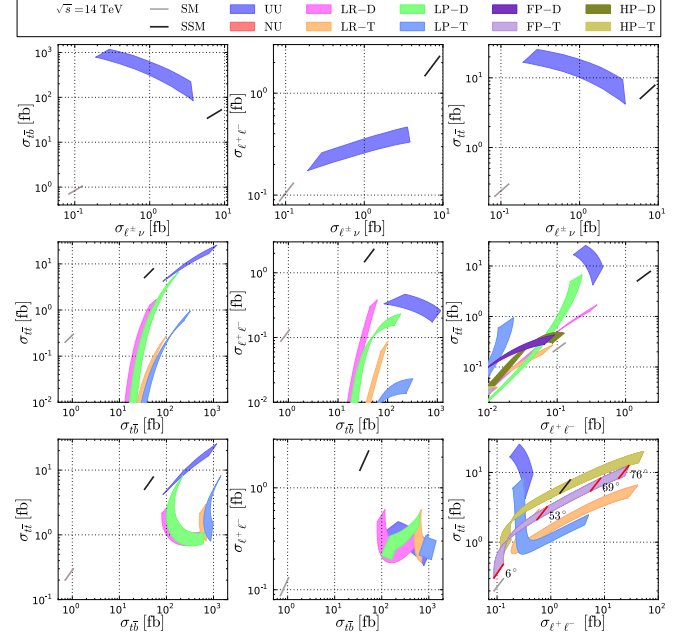


FIG. 2: Correlations of CC and NC lepton (e, μ) and third-generation quark cross sections for fixed $M_{W'} = 3.0 \pm 0.1$ TeV (top, center) and $M_{Z'} = 3.0 \pm 0.1$ TeV (top, bottom).

and do not overlap with those of the SSM for which we also assume $M_{W'} = M_{Z'}$, it would therefore be easily identifiable. The plots in the other two lines do not involve the lepton-neutrino channel, and we can therefore show predictions for all G(221) models except for the excluded NU model and the HP and FP models, which are only accessible in the NC channels. It is clear that the overlap is very much reduced compared to Fig. 1, making a unique identification of the underlying gauge group possible in almost all cases. Even doublet (D) and triplet (T) Higgs fields can now be distinguished, but this requires the observation of at least one CC channel and/or knowledge of the W' mass. The NC channels are obviously most useful if the Z' mass is known (bottom right) and exhibit then already by themselves a large discriminatory power of the gauge group. It would in particular be sufficient to measure the $t\bar{t}$ and $\ell^+\ell^-$ cross sections with a precision of about 30%. The position of these measurements in the correlation plane would then also give information on the remaining model parameters, in particular the mixing angle ϕ at the first breaking stage (cf. the red iso-lines in the bottom-right plots of Figs. 2 and 3).

A similar analysis is performed in Fig. 3, where the W' (top, center) and Z' (top, bottom) mass is now assumed to be 4.0 ± 0.1 TeV, respectively. This larger mass naturally leads to cross sections that are reduced by about one order of magnitude with respect to those in Fig. 2, but they remain observable and larger than the SM background. For this higher mass, the NU model is no longer

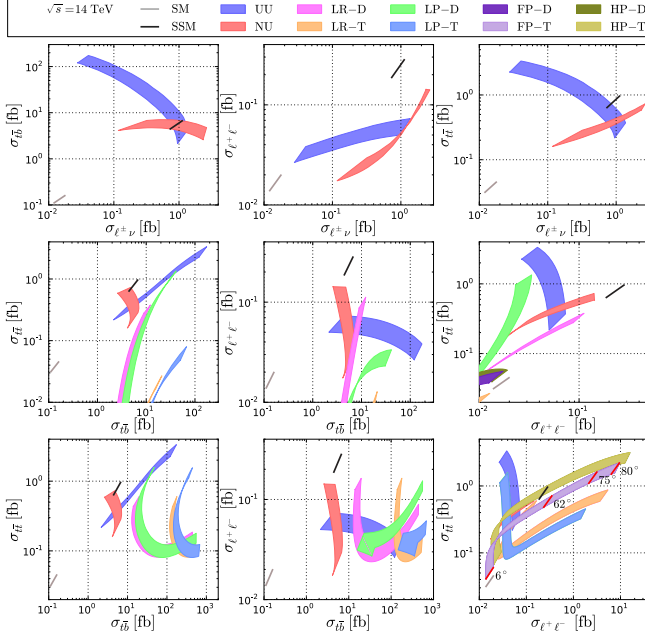


FIG. 3: Correlations of CC and NC lepton and third-generation quark cross sections for fixed $M_{W'} = 4.0 \pm 0.1$ TeV (top, center) and $M_{Z'} = 4.0 \pm 0.1$ TeV (top, bottom).

excluded by the global analysis and therefore added to the plots. Correlating the lepton-neutrino with the $t\bar{b}$ and/or NC channels (top) makes it then clearly distinct from the UU model. Since the third generation couples differently from the other two in the NU model, its predictions for third-generation quark cross sections lead to almost constant lines or point-like areas when correlated with the lepton cross sections or each other.

Conversely, agreement of the experimental measurements with the SM predictions in Figs. 1-3 would allow to considerably constrain the parameter space of the different G(221) models or even to exclude the corresponding new gauge boson masses altogether.

For completeness, we also show predictions for the LHC operating at $\sqrt{s} = 8$ TeV in Figs. 4 and 5. If one extrapolates the current LHC luminosity performance until the end of 2012, one may estimate $60\text{--}80 \text{ fb}^{-1}$ so that measuring cross sections down to 10^{-2} fb is not unrealistic. The cross sections for resonances with a mass of 4 TeV turn out to be too small and we therefore fix the mass to $3 \pm 0.1 \text{ TeV}$ in Fig. 5. The NU model can thus not be identified with data taken at 8 TeV. Inspecting Fig. 5, new gauge bosons with a mass of 3 TeV in the UU model could already be distinguished from the SSM if one of the third generation quark channels is measurable (top). If both the neutral and charged current channels are measurable, one can also distinguish it from the LR-D and LP-D models without making any assumptions on the right-handed neutrino (center). Distinguishing different “doublet” (LR-D, LP-D, ...) and “triplet” (LR-T,

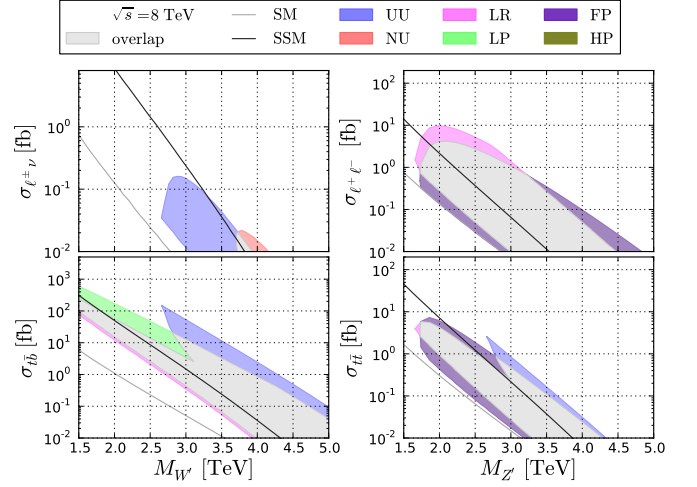


FIG. 4: Same as Fig. 1 for LHC at $\sqrt{s} = 8$ TeV.

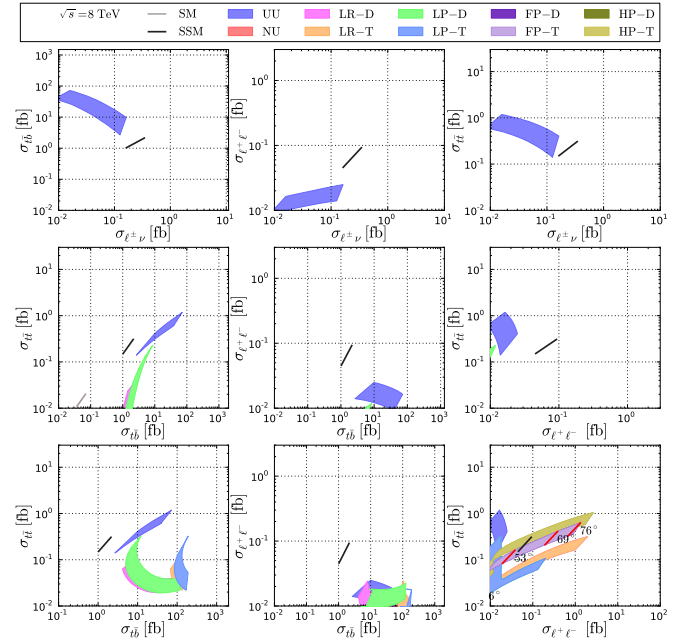


FIG. 5: Same as Fig. 2 for LHC at $\sqrt{s} = 8$ TeV.

LP-T, ...) models is partly possible using the $(\sigma_{t\bar{t}}, \sigma_{t\bar{b}})$ correlation (bottom left). Furthermore, depending on the precision of the Z' mass measurement, it might also be feasible when correlating the neutral current lepton channel with the $t\bar{t}$ channel (bottom right) and then even lead to a first measurement of the mixing angle ϕ .

CONCLUSIONS

In conclusion, we have proposed a novel and powerful method to distinguish general $SU(2) \times SU(2) \times U(1)$ models, motivated experimentally, *e.g.*, by the observation of

neutrino masses and theoretically as an intermediate step towards the grand unification of the SM gauge groups. The total cross sections of the predicted charged and neutral gauge bosons decaying into leptons and third-generation quarks were confirmed to be accessible at the LHC up to masses of 5 TeV within the range of parameters allowed by a recent global analysis of low-energy and LEP constraints. Individually, these cross sections did, however, not allow for the unique identification of the underlying G(221) model. With a Monte Carlo simulation and after applying realistic experimental cuts, we demonstrated that this does become possible by correlating the charged and neutral current cross sections of leptons and third-generation quarks, assuming only that the mass of either the W' or the Z' boson has been measured with a conservative uncertainty. The mixing angle of the high-energy symmetry breaking stage will then also become measurable. The correlations of two observables work nicely here because we only have two (three) free parameters describing all the G(221) models. In the general case of models with more parameters the identification of suitable subsets of correlated observables would represent a first step towards a global analysis of the parameter space.

Note added:

After publication of this article four related articles have appeared discussing the LHC phenomenology of models with an additional SU(2) group [25–28].

Acknowledgments

We thank R. Bonciani for his contributions during the initial stages of this work and B. Clement, B. Dechenaux, P.A. Delsart, T. Junk, F. Ledroit, F. Lyonnet and A. Wingerter for useful discussions. This work has been supported by a Ph.D. fellowship of the French Ministry for Education and Research and by the Theory-LHC-France initiative of the CNRS/IN2P3.

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